ON THE RELAXATION OF A TURBULENT BOUNDARY LAYER AFTER AN ENCOUNTER WITH A FORWARD FACING STEP

by

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SUMMARY

An experiment has been performed in a low speed wind-tunnel to determine the mean flow relaxation characteristics for a zero pressure gradient turbulent boundary layer which encounters a small forward facing step. Of primary interest is the behaviour of the local wall shear stress downstream of the step and this has been determined by the use of a series of buried hot-wire gauges. The mean velocity profiles downstream of the step have been measured using a traversing Pitot tube and these have indicated that a step produces very marked changes in the distribution for both the inner and outer regions of the flow. The results shed new light upon the variation of wall shear stress downstream of a severe perturbation and also indicate that the use of Preston tube or Clauser chart methods for the determination of wall shear may lead to very large errors. As a consistency check on the data, estimates of the step drag based upon force-momentum conservation considerations have been compared with previously published drag balance measurements. The agreement between the data sets is very good.

NOTATION

A,B	constants in the semi-logarithmic inner region
$\bar{A},\bar{B}$	constants in the buried wire gauge calibration
C_D	drag coefficient of the step based upon step frontal area and free-stream dynamic pressure ($\frac{1}{2}\rho U_\infty^2$)
C_f	skin friction coefficient ($\tau_w/\frac{1}{2}\rho U_\infty^2$)
C_p	pressure coefficient ($p-p_\infty/\frac{1}{2}\rho U_\infty^2$)
E	output voltage from hot-wire bridge
H	boundary layer shape factor
h	step height
p	static pressure
R	Reynolds number
T	temperature
ΔT	difference between hot-wire operating temperature and the flow reference temperature
u	velocity in the x direction
U_τ	friction velocity $(\tau_w/\rho)^{\frac{1}{2}}$
x,y	coordinate system with the origin at the step location - see figure 1
δ	height above the wall at which u reaches 99.5% of the free-stream speed
θ	boundary layer momentum thickness
ν	kinematic viscosity
ρ	density
τ	shear stress

Subscripts

w	at the wall
∞	in the undisturbed free-stream

INTRODUCTION

In recent years there has been considerable interest in the possibility of direct manipulation of the structure of turbulent boundary layers with a view to reducing the overall drag of a given surface. So far two methods, which have potential aeronautical applications and which have been shown to produce modest but repeatable drag reductions for attached fully turbulent boundary layers, have been identified. The first involves the use of small streamwise wall ribs, or riblets (Walsh[1]) whilst the second involves the use of single transverse devices which locally break up the large eddies in the outer part of the boundary layer (Hefner et al[2]). These latter devices are collectively known as LEBU's - standing for Large Eddy Break Up. It appears that, used in conjunction, these turbulence modifiers could produce overall drag reductions of order 5 - 20% for typical civil aircraft configurations. This level of reduction may appear to be rather small but in a review paper Bushnell[3] has estimated that a 20% reduction in fuselage skin friction for the whole of the United States CTOL civil aircraft fleet would result in an annual saving of almost one billion dollars in fuel costs alone. A financial incentive of this magnitude should provide a powerful argument in support of continued research into the fundamental aspects of turbulent boundary layer structure.

It seems that the wall riblets and the LEBUs operate on entirely different principles. In the former case the drag reduction is associated with the riblet and is felt directly by the riblet. Therefore a surface will have minimum drag if it is completely covered with riblets. A LEBU is, however, an isolated disturbance which itself carries a drag penalty. The immediate effect of the LEBU is to reduce the wall shear stress downstream of the device. This perturbed wall shear gradually relaxes with increasing distance downstream and, consequently, a successful LEBU is one for which the device drag plus the integrated wall shear is less than the integrated wall shear for the undisturbed flow. To date, however, much of the LEBU work has served mainly to highlight the generally poor level of understanding of the behaviour of non-equilibrium boundary layer flows. In particular Hefner et al[2] report that there is a dearth of definitive (reliable) data for initially equilibrium turbulent boundary layers relaxing fully to a new equilibrium, or self-preserving, states after having experienced an abrupt change in boundary condition. Clearly such a relaxation process is of key importance in a drag reducing system since this is the region in which the wall shear stress falls below its undisturbed value. It is, primarily, this basic lack of information which has prompted the present investigation.

The experiment to be described in this paper reveals some of the features of the process by which a fully turbulent boundary layer, which has initially developed under conditions of zero pressure gradient, returns to an equilibrium state after it has encountered a small forward facing step. This particular flow is of interest for three basic reasons. In the first instance the step acts as a one parameter LEBU device since it constitutes a 'change in boundary condition' for the flow which results in a highly localised and extremely severe pressure perturbation near the surface. Therefore, in the terms suggested by Hefner, the resulting relaxation process is relevant to physics of LEBUs in general, despite the fact that, in this case, the pressure force on the step is too large for there to be a net reduction in drag. The basic drag of the step forms the second reason for interest in this flow since the forward facing step constitutes a surface imperfection, or excresence, which is commonly found in aeronautical applications. Whilst it has been known for many years that this type of imperfection can produce significant drag increments there is still only a very limited amount of design information available - see Young and Patterson[4]. The results of this experiment will supplement this data base. Finally, in relation to the basic problem of measuring local wall shear stresses, there are now commercially available hot-film gauges which can be fixed directly to the surface under investigation. Since these gauges have finite thickness the upstream edge will constitute a forward facing step which must disturb the flow locally. Therefore, before these gauges can be used with confidence, it is necessary to quantify the effects of the step on the flow at the point at which the measurement of wall shear is made.

THE EXPERIMENTAL ARRANGEMENT AND TEST CONDITIONS

The experimental arrangement and notation are summarised in figure 1. Tests were performed in a low-speed wind tunnel with a working section 11" wide and 7" high. In order to obtain a thick viscous layer the test boundary layer was that generated on the floor of the working section. To smooth out any spanwise non-uniformity introduced by natural transition this boundary layer was tripped by a transverse wire 0.060" in diameter placed 10" upstream of the step. Part of the floor of the wind-tunnel consisted of an aluminium plate 36" long and 15" wide which was held in place by four screw jacks. These jacks could change the level of this section of the floor in relation to the upstream section which was fixed relative to the tunnel contraction cone. Normally these jacks are used to enable the plate to be set flush with the rest of the floor or to be lowered for removal and replacement. However, for the present experiment the side walls and roof were cut so that the portion of the working section normally in contact with the plate could be moved relative to the rest of the tunnel. In this way the upstream edge of the aluminium plate served as the step whose height could be set to any desired level simply by manipulating the jacks. Moreover, since the walls and roof moved with the plate, the geometrical cross-sectional area of the working section was constant at all streamwise locations irrespective of the height of the step. This meant that the dynamic pressure of the free-stream would not change in the vicinity of the step as a result of a continuity constraint imposed by the tunnel walls. An additional feature of this tunnel was that one of the sidewalls could be moved, as indicated in figure 1. Therefore it was possible, by using the wall to balance far upstream and far downstream static pressures, to ensure that flow beyond the step was relaxing under conditions which were the same as those in which the flow ahead of the step had developed.

Reference conditions for the tests were determined by a wall mounted Pitot tube and a static pressure tapping on the floor of the tunnel - these being positioned 4.00" and 2.32" upstream of the step. Static pressures were measured on the test surface at various positions downstream of the reference static tapping. Downstream of the step (i.e. on the removable aluminium plate) a series of flush mounted hot-wire gauges of the type described by Rubesin et al[5] were mounted at the positions indicated in figure 1. These were used to measure local wall shear-stress and were run in the constant temperature mode with power being provided by a bank of conventional hot-wire anemometer bridges. Finally, the tunnel has a traversing mechanism which allowed the measurement of the mean velocity profiles with a small flattened Pitot tube.

The free-stream conditions and the step heights used in these tests are summarised in table 1.

THE CALIBRATION OF THE FLUSH MOUNTED HOT-WIRES

One of the most significant features of the present investigation was the use of flush mounted,or buried, hot-wire gauges for the measurement of wall shear-stress. Although these devices measure the stress 'indirectly' i.e. through a relation linking stress to convective heat transfer rate, their performance does not require the mean velocity profile to exhibit any special features e.g. a universal law of the wall. Since the profiles under investigation were initially non-equilibrium it was felt that the use of Preston tubes or Clauser charts was essentially unjustifiable and that the hot-wire gauge was the only practical alternative.

The gauges were calibrated 'in situ' using the wall shear-stress distribution for the undisturbed boundary as determined by Preston tubes. A typical calibration is presented in figure 2. As suggested by Rubesin et al[5] the calibration law is of the form

$$\frac{E^2}{\Delta T} = \bar{A}\tau_w^{1/3} + \bar{B}.$$

In figure 2, however, this relation is inverted and presented as τ_w versus $E^2/\Delta T$. This direct form immediately reveals an inherent problem for this type of gauge, namely the extreme sensitivity of the indicated value for shear stress to errors in $E^2/\Delta T$. In the example given it is clear that a 1% error in $E^2/\Delta T$ leads to a 20% error in τ_w. Consequently, it is essential that $E^2/\Delta T$ be known to a high degree of accuracy. In principle, it is possible to measure the E^2 component to within the necessary limits but the evaluation of ΔT possess a more serious problem. In a closed wind-tunnel the temperature of the air tends to increase with time and there is also a variation of the temperature of the aluminium plate. Since the maximum operating temperature of the wire was approximately 60°C (determined by the properties of the substrate) and the ambient temperature of the air within the tunnel was about 20°C, then to guarantee the accuracy of the shear stress to within ±5% requires that the surface reference temperature for the gauge must be known to within 0.1°C. In the present series of tests this surface reference temperature was obtained by using the most downstream hot-wire gauge as a resistance thermometer. Despite this, repeated calibrations indicated that the shear stress accuracy was limited to ±10%. However, it was felt that in future tests this figure could well be improved upon.

EXPERIMENTAL RESULTS

a) Undisturbed Boundary Layer

The variation of skin friction coefficient (Preston tube), momentum thickness and shape factor with position for a fixed free-stream unit Reynolds number are presented in figures 3,4 and 5 respectively. Figures 6 and 7 show the velocity profiles plotted in 'law of the wall' form and in 'velocity defect' form. These results show that the undisturbed boundary layer exhibits the usual mean flow characteristics of a turbulent zero-pressure gradient boundary layer.

b) Surface Pressure Distribution

The surface pressure distributions for various step heights are shown in figure 8 where the streamwise coordinate x has been normalised with respect to the step height, h. Also shown for comparison is the result according to inviscid flow theory - see Milne-Thomson[6]. It is interesting to note that, despite the fact that the pressure at a fixed value of x/h increases slightly with increasing h/θ, the surface pressure distribution closely follows the behaviour of the inviscid solution. These distributions clearly show the strength of the pressure perturbation introduced by the step. However, it should also be appreciated that this perturbation decays very rapidly with distance normal to the surface. The inviscid solution decay rate suggests that the pressure perturbation will have virtually disappeared at the edge of the boundary layer. Therefore, in the vicinity of the step, the assumption that $\partial p/\partial y$ is equal to zero within the boundary layer is not applicable. As a result of this difficulty no skin friction or velocity profile measurements were made at an x/h of less than 6.

c) Wall Shear Stress Distribution

The distribution of wall shear stress for the various step heights, as indicated by the buried hot-wire gauges, is given in figure 9. Perhaps the most notable feature is the complete insensitivity of τ_w to the height of the step. In all cases the wall shear-stress has returned to within ±10% of the undisturbed value by the first measuring station (0.768" downstream of the step).

d) Momentum Thickness Reynolds Number

Figure 10 shows the variation of momentum thickness Reynolds number with downstream position for several step heights. Although the data exhibit a little scatter it is quite clear that, downstream of the area in which the step produces a significant wall pressure perturbation, the development of R_θ is parallel to that for the no-step condition. Far downstream from the step the pressure gradient is very small and tending to zero, therefore, from the two-dimensional momentum integral equation -

$$\frac{dR_\theta}{dR_x} = \frac{C_f}{2} .$$

Hence the parallel trends for R_θ versus R_x indicate that the values of C_f (and hence τ_w) have returned to the undisturbed levels. This is in agreement with the results from the buried hot-wire gauges (figure 9).

e) Mean Velocity Profiles

An overall impression of the effect of the step on the mean velocity profiles may be obtained from a plot of shape factor, H, versus distance downstream of the step. This is given in figure 11. These data show that the greater the step height the larger the distortion suffered by the mean velocity profile. However, the relaxation length does not appear to depend upon step height. The data show that, no matter what the value of h, the shape factor has returned to the undisturbed value approximately 10 inches, or 25δ, downstream of the step. As an example of the actual velocity profiles figures 12 and 13 show the relaxation process for a step height of 0.124" in both 'law of the wall' and 'velocity defect' form. In both these cases the wall shear-stress used for the data reduction is that given by the buried hot-wire gauges. It is clear that, in both figures, the initial deviation from the undisturbed distributions is large but that the relaxation process is complete at 10" from the step.

DISCUSSION

The use of buried hot-wire gauges for the measurement of local wall shear-stress has shed new light on the relaxation process for a boundary layer perturbed by a step. Data presented in figure 9 show that even the largest step considered in this investigation failed to produce a detectable deviation from the undisturbed level even though the first measuring station was only 6.h downstream of the step. Therefore, it appears that any relaxation of the wall shear-stress is very rapid indeed - of the order 1 to 2 boundary layer thicknesses rather than the 20 to 30δ suggested by the survey of Hefner et al[2]. It should be noted, however, that the present findings are in good agreement with the experiments of Kiske et al[7] who measured wall shear-stress distributions downstream of roughness jumps and sudden enlargements in channels. Their results also show that significant changes in τ_w only occur in the immediate vicinity of the perturbation. In the present case we note that the mean boundary layer profiles are considerably altered by the presence of the step and that the relaxation length for both 'inner' and 'outer' regions is of order 25δ. From figure 12 it can be seen that although there is a region close to the wall which is of the form -

$$\frac{U}{U_\tau} = A \ \mathrm{LOG} \ \left(\frac{U_\tau y}{\nu}\right) + B$$

The values of A and B do not correspond to the generally accepted 'universal' values until the relaxation process for the mean profile is complete. Therefore if the wall shear-stress in the vicinity of the step had been determined by the Preston tube or Clauser plot methods then C_f would have been seriously underestimated. For example, using the first measuring station data given in figure 12, these techniques would yield a skin friction coefficient approximately 30% lower than that indicated by the buried hot-wire gauge at the same location. Since the uncertainty of the buried hot-wire gauge is only ±10% it seems unlikely that this difference could be accounted for in terms of measurement error. Moreover, the apparent discrepancies in the use of the Preston tube and Clauser methods in the present case are similar in magnitude to those noted by Kiske et al[7] in their experiments. The clear implication is that, in work on LEBUs or other drag reducing devices, skin friction in the immediate vicinity of the perturbation should not be determined by either standard Preston tube or Clauser chart methods.

As stated in the introduction there is some interest in the forward facing step as a source of extra drag, i.e. excrescence drag, in aeronautical applications. Previous measurements of the drag of steps have been carried out by mounting steps on a very sensitive drag balance and data have been presented by Gaudet and Johnson[8]. In the present case consideration of the force and momentum balance for a control volume which includes the step but extends sufficiently far upstream, downstream and normal to the test surface for the static pressure to be uniform over those faces of the volume which are in the fluid leads to the conclusion that -

$$\frac{C_D}{C_f} = \frac{2}{C_f}\frac{\Delta\theta}{h}$$

In this relation C_D is the drag coefficient of the step based upon the step frontal area, C_f is the undisturbed skin friction coefficient at the step location, h is the step height and $\Delta\theta$ is the difference between the disturbed and undisturbed momentum thickness at the downstream end of the control volume. The above relation was used to compute the drag of the step from the data presented in figure 10 and the results are presented in figure 14 in the form C_D/C_f versus log $(U_\tau h/\nu)$. Also shown in figure 14 is the empirical relation proposed by Gaudet and Johnson[8] together with the scatter bands for the data upon which this relation was based. The present results lie well within the bounds of the Gaudet and Johnson results and, in general, support the balance data and the suggested empirical relation.

Finally, regarding the use of commercially produced 'glue on' hot-film probes for the measurement of local wall shear-stress, the results presented in figure 9 suggest that, provided the thickness of the substrate is such that -

$$70 < \frac{U_\tau h}{\nu} < 250$$

the indicated τ_w will be equal to the shear-stress of the undisturbed surface (±10%). In view of the considerable convenience of the 'glue on' type probe compared with the flush mounted type used in this experiment this result is of considerable practical importance.

CONCLUSION

This experimental investigation has shown that a small forward facing step produces a significant change in the mean flow characteristics of a zero pressure gradient turbulent boundary layer. The step induces a pressure perturbation in the vicinity of the wall whose strength increases with increasing values of the step height to boundary layer thickness ratio. This pressure perturbation decreases rapidly with increasing downstream distance and, for the step heights considered, undisturbed pressure levels are regained at between 2 and 10 boundary layer thicknesses downstream of the step. The initial distortion of the mean velocity profiles also increases with increasing step height but the relaxation process takes place over a length of approximately 25δ irrespective of the step height. By measuring the wall shear-stress in the relaxation zone with buried hot-wire gauges it has been shown that, when plotted in inner region variables the velocity profile close to the wall exhibits a semi-logarithmic behaviour but this does not correspond to the 'universal' distribution. The data indicate that the universal law of the wall is regained after 25δ. Results obtained from the buried wire gauges also indicate that the wall shear-stress recovers its undisturbed value very rapidly - in this experiment the recovery distance was less than 2δ. This is a disappointing result from the drag reduction point of view. In addition these observations suggest that the use of standard Preston tube or Clauser chart methods for the estimation of wall shear in perturbed boundary layers may lead to very large errors. Consequently, these techniques are not recommended for use in evaluating the performance of LEBU devices. The results of this investigation do, however, indicate that accurate wall shear-stress measurements can be made with 'glue-on' hot-film gauges provided that the substrate thickness is such that it lies within the 'law of the wall' region for the undisturbed boundary layer.

Finally, the detailed measurements of the boundary layer relaxation process have been used to evaluate the drag of the steps from considerations of the force-momentum exchange taking place within a large control volume. The inferred values have been found to be in good agreement with previously published data obtained by an accurate drag balance technique.

ACKNOWLEDGEMENT

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Table 1 - A summary of the test conditions

Free-stream unit Reynolds number	0.444×10^5 (1/ins)
undisturbed boundary layer thickness at step location	0.410 (ins)
undisturbed momentum thickness at step location	0.034 (ins)
undisturbed skin friction coefficient at step location	0.00405

step height h(ins)	h/δ_{step}	$(\frac{U_\tau h}{\nu})_{step}$
0.037	0.090	74
0.070	0.171	140
0.097	0.237	194
0.124	0.302	248

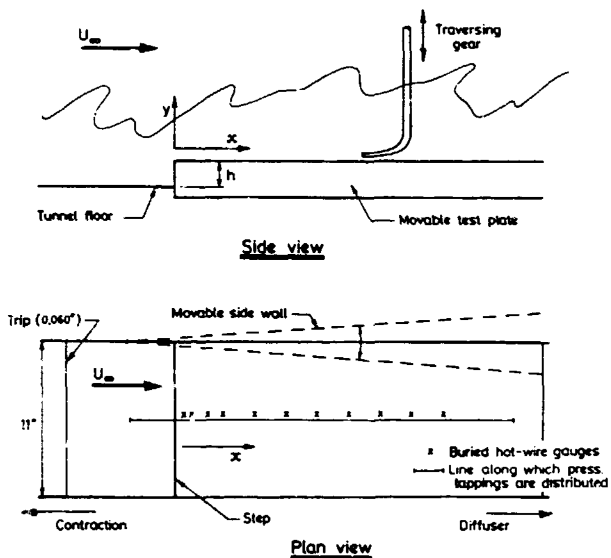

Figure 1. The experimental arrangement and notation.

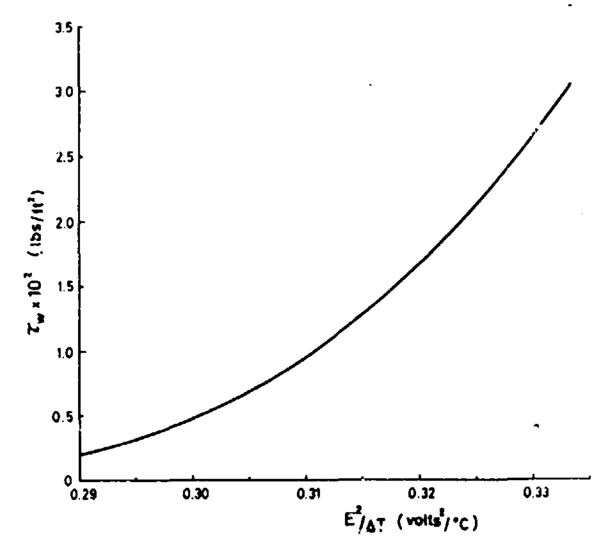

Figure 2. Calibration curve for the buried hot-wire gauge at $x = 0.786$ inches

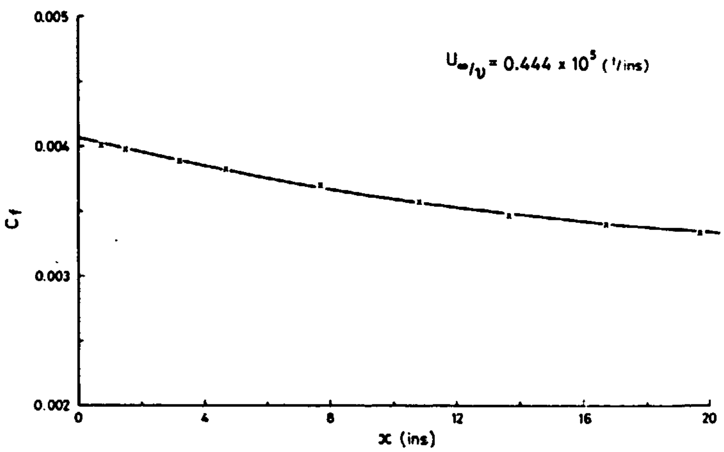

Figure 3. The variation of the skin friction coefficient with position for the undisturbed boundary layer.

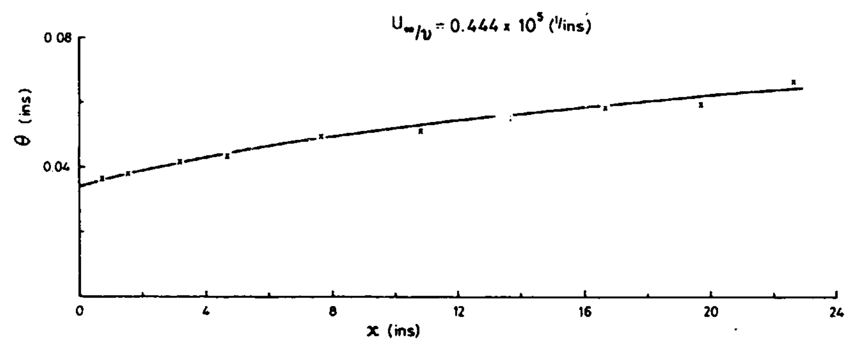

Figure 4. The development of momentum thickness in the undisturbed boundary layer.

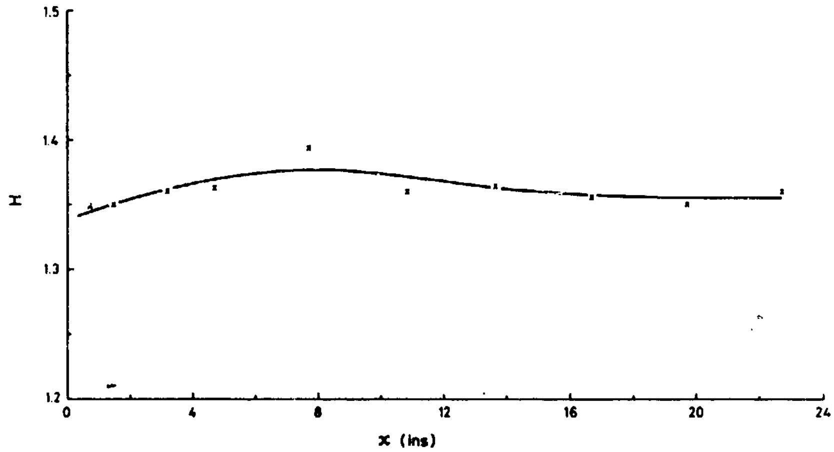

Figure 5. The development of the shape factor in the undisturbed boundary layer.

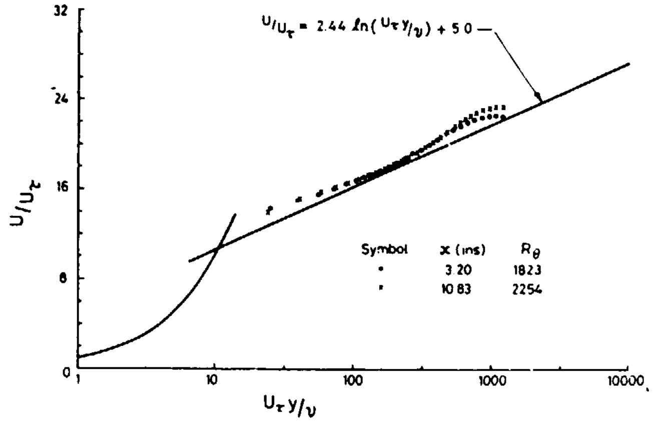

Figure 6. The mean velocity distribution through the undisturbed boundary layer in inner layer coordinates.

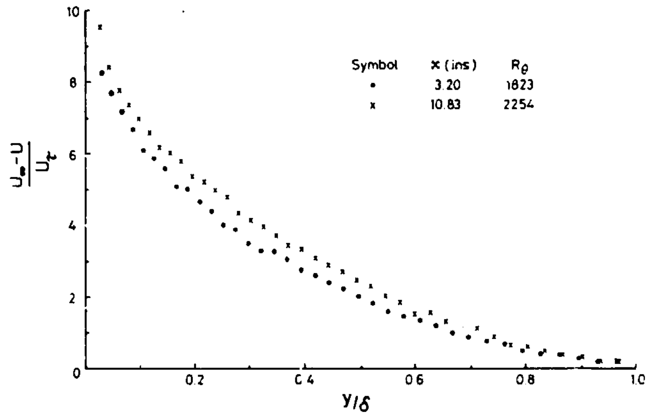

Figure 7. The mean velocity distribution through the undisturbed boundary layer in velocity defect form.

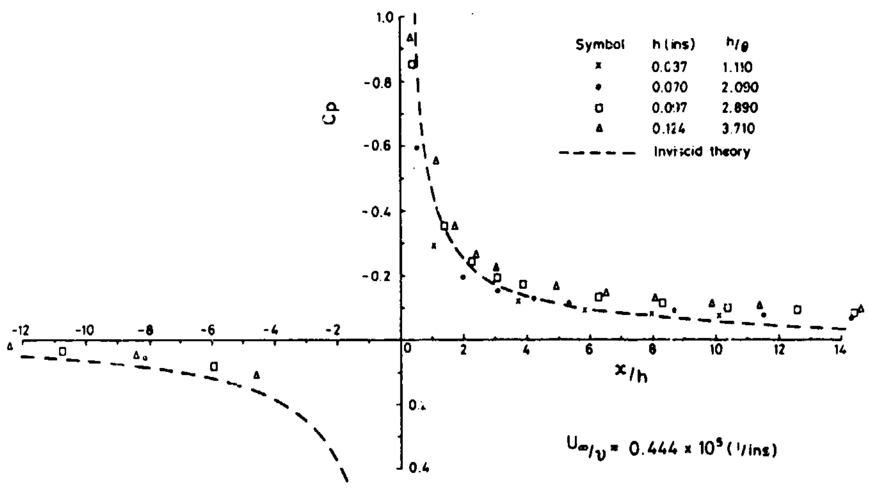

Figure 8. The variation of surface pressure for various step heights at fixed free stream unit Reynolds number.

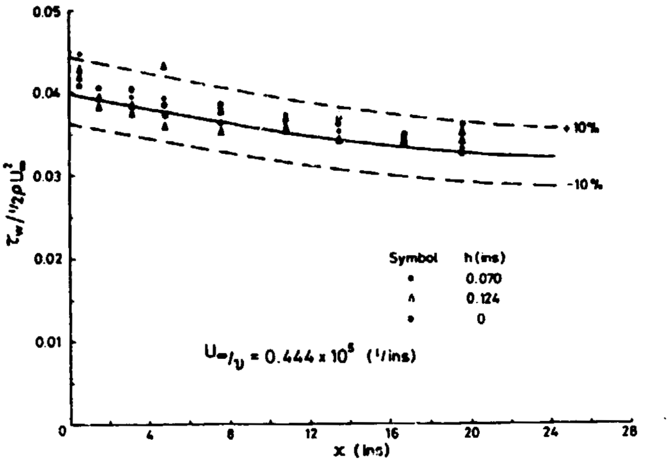

Figure 9. The variation of wall shear stress downstream of the step as indicated by the buried hot-wire gauges.

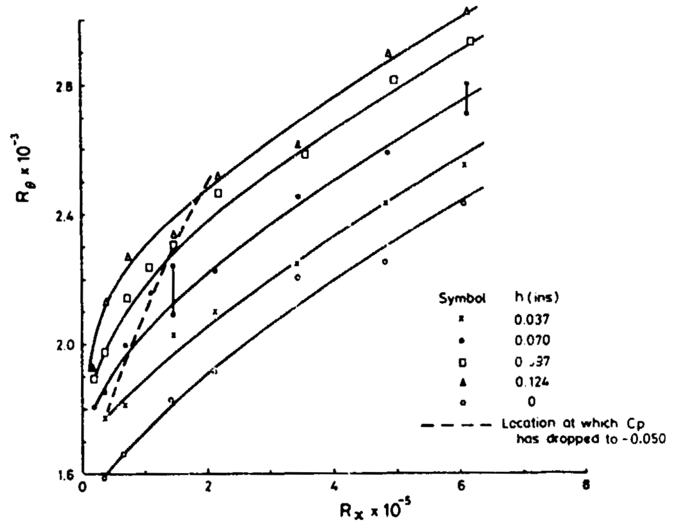

Figure 10. The development of the momentum thickness Reynolds number downstream of the step.

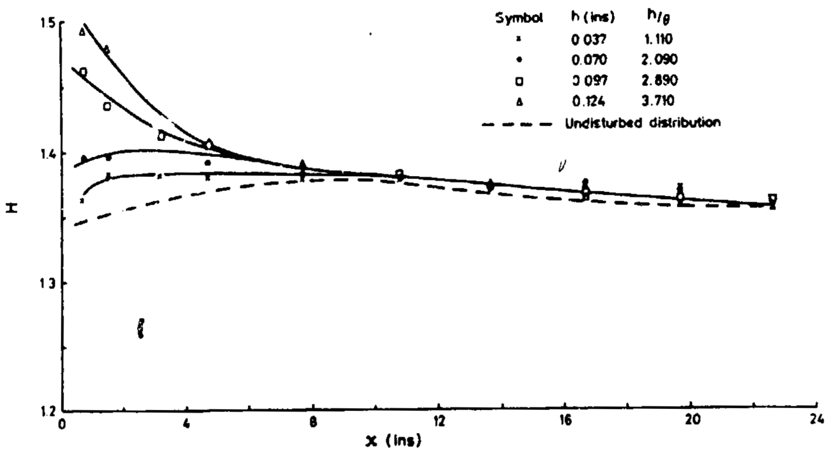

Figure 11. The relaxation of the profile shape factor downstream of the step.

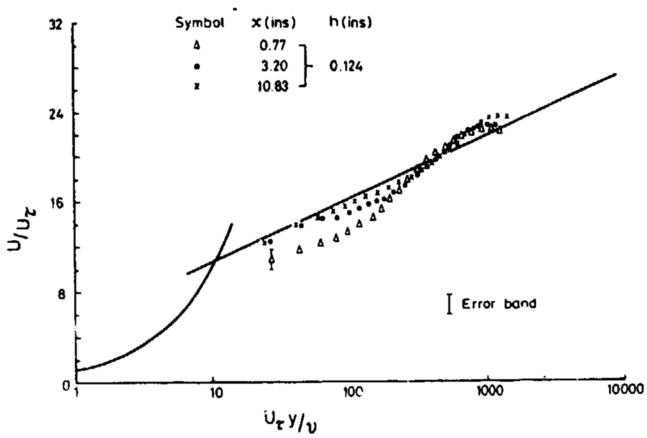

Figure 1... The relaxation of the mean velocity profile in inner layer coordinates.

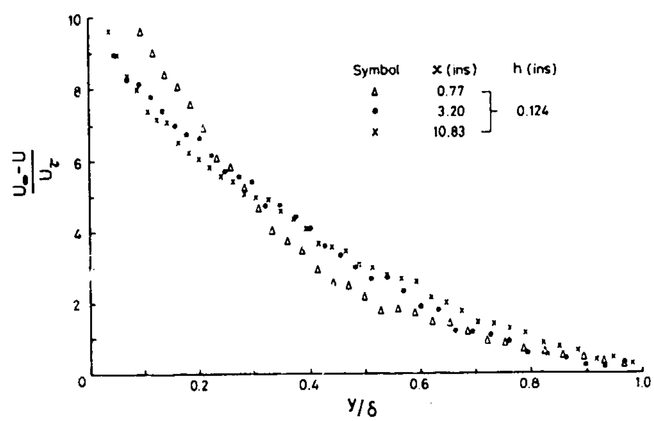

Figure 13. The relaxation of the mean velocity profile in velocity defect form.

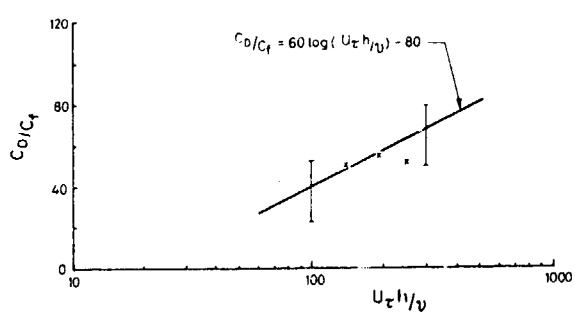

Figure 14. The dependence of step drag upon step height.